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High-Voltage Power Electronic Substations

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The preceding sections on gas-insulated substations (GIS), air-insulated substations (AIS), and high-voltage switching equipment apply in principle also to the ac circuits in high-voltage power electronic substations. This section focuses on the specifics of power electronics as applied in substations for power transmission purposes.

The dramatic development of power electronics in the past decades has led to significant progress in electric power transmission technology, resulting in special types of transmission systems, which require special kinds of substations. The most important high-voltage power electronic substations are converter stations, above all for high-voltage direct current (HVDC) transmission systems, and controllers for flexible ac transmission systems (FACTS).

High-voltage power electronic substations consist essentially of the main power electronic equipment, i.e., converter valves and FACTS controllers with their dedicated cooling systems. Furthermore, in addition to the familiar components of conventional substations covered in the preceding sections, there are also converter transformers and reactive power compensation equipment, including harmonic filters, buildings, and auxiliaries.

Most high-voltage power electronic substations are air insulated, although some use combinations of air and gas insulation. Typically, passive harmonic filters and reactive power compensation equipment are air insulated and outdoors, while power electronic equipment (converter valves, FACTS controllers), control and protection electronics, active filters, and most communication and auxiliary systems are air insulated, but indoors.

Basic community considerations, grounding, lightning protection, seismic protection, and general fire protection requirements apply as with other substations. In addition, high-voltage power electronic substations may emit electric and acoustic noise and therefore require special shielding. Extra fire protection is applied as a special precaution because of the high power density in the electronic circuits, although the individual components of today are mostly nonflammable and the materials used for insulation or barriers within the power electronic equipment are flame retardant.

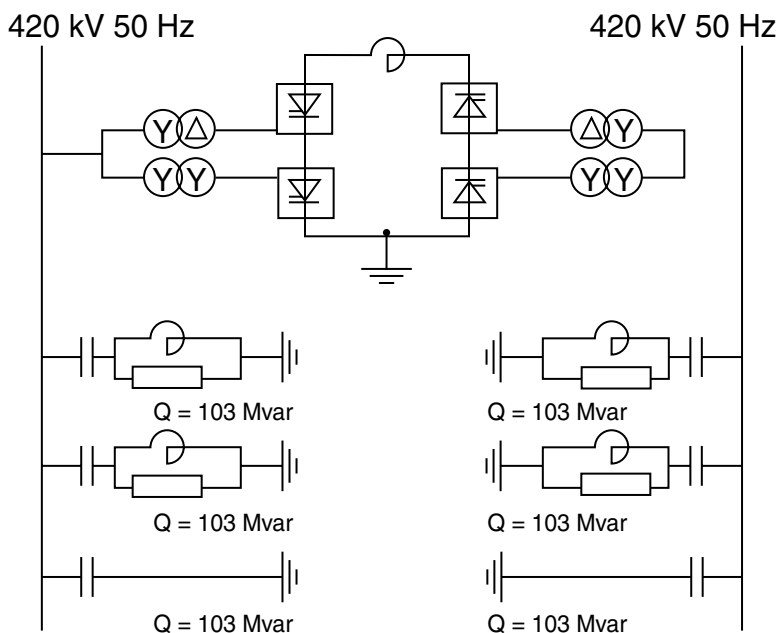


FIGURE 5.1 Schematic diagram of an HVDC back-to-back converter station, rated 600 MW.

International technical societies like IEEE, IEC, and CIGRE continue to develop technical standards, disseminate information, maintain statistics, and facilitate the exchange of know-how in this high-tech power engineering field. Within the IEEE, the group that deals with high-voltage power electronic substations is the IEEE Power Engineering Society (PES) Substations Committee, High Voltage Power Electronics Stations Subcommittee. On the Internet, it can be reached through the IEEE site (www.ieee.org).

5.1 Converter Stations (HVDC)

Power converters make possible the exchange of power between systems with different constant or variable frequencies. The most common converter stations are ac-dc converters for high-voltage direct current (HVDC) transmission. HVDC offers frequency- and phase-independent short- or long-distance overhead or underground bulk power transmission with fast controllability. Two basic types of HVDC converter stations exist: back-to-back ac-dc-ac converter stations and long-distance dc transmission terminal stations.

Back-to-back converters are used to transmit power between nonsynchronous ac systems. Such connections exist, for example, between the western and eastern grids of North America, with the ERCOT system of Texas, with the grid of Quebec, and between the 50-Hz and 60-Hz grids in South America and Japan. With these back-to-back HVDC converters, the dc voltage and current ratings are chosen to yield optimum converter costs. This aspect results in relatively low dc voltages, up to about 200 kV, at power ratings up to several hundred megawatts. Figure 5.1 shows the schematic diagram of an HVDC back-to-back converter station with a dc smoothing reactor and reactive power compensation elements (including ac harmonic filters) on both ac buses. The term back-to-back indicates that rectifier (ac to dc) and inverter (dc to ac) are located in the same station.

Long-distance dc transmission terminal stations terminate dc overhead lines or cables and link them to ac buses and systems. Their converter voltages are governed by transmission efficiency considerations and can exceed 1 million V (± 500 kV) with power ratings up to several thousands of megawatts. Typically,

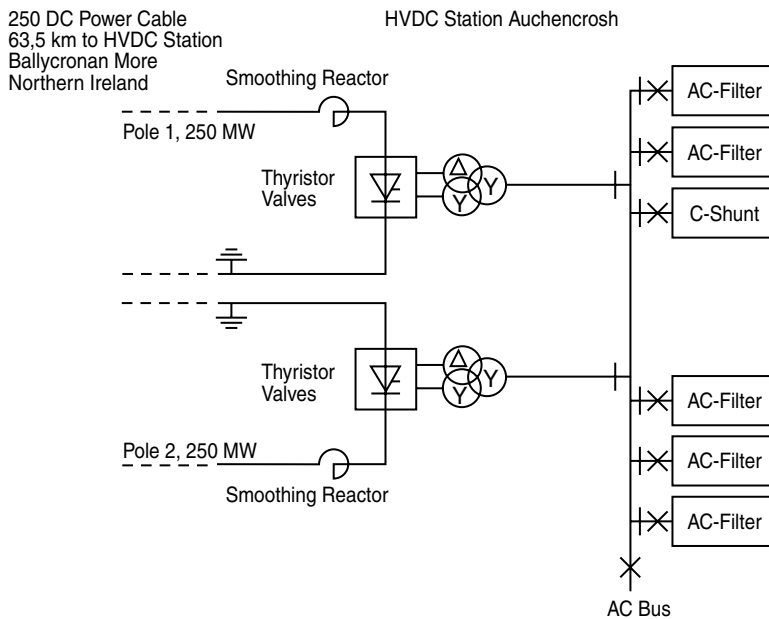


FIGURE 5.2 Schematic diagram of the Auchencrosh terminal station of the Scotland-Ireland HVDC cable transmission.

in large HVDC terminals, the two poles of a bipolar system can be operated independently, so that in case of component or equipment failures on one pole, power transmission with a part of the total rating can still be maintained. Figure 5.2 shows the schematic diagram of one such bipolar HVDC sea cable link with two 250-MW converter poles and 250-kV dc cables.

Most HVDC converters of today are line-commutated 12-pulse converters. Figure 5.3 shows a typical 12-pulse bridge circuit using delta and wye transformer windings, which eliminate some of the harmonics typical for a 6-pulse Graetz bridge converter. The harmonic currents remaining are absorbed by adequately designed ac harmonic filters that prevent these currents from entering the power systems. At the same time, these ac filters meet most or all of the reactive power demand of the converters. Converter stations connected to dc lines often need dc harmonic filters as well. Traditionally, passive filters have been used, consisting of passive components like capacitors, reactors, and resistors. More recently, because of their superior performance, active (electronic) ac and dc harmonic filters [1–5] — as a supplement to passive filters — using IGBTs (insulated gate bipolar transistors) have been successfully implemented in some HVDC projects. IGBTs have also led to the recent development of self-commutated converters, also called voltage-sourced converters [6–8]. They do not need reactive power from the grid and require less harmonic filtering.

The ac system or systems to which a converter station is connected significantly impact its design in many ways. This is true for harmonic filters, reactive power compensation devices, fault duties, and insulation coordination. Weak ac systems (i.e., with low short-circuit ratios) represent special challenges for the design of HVDC converters [9]. Some stations include temporary overvoltage limiting devices consisting of MOV (metal oxide varistors) arresters with forced cooling for permanent connection, or using fast insertion switches [10].

HVDC systems, long-distance transmissions in particular, require extensive voltage insulation coordination, which can not be limited to the converter stations themselves. It is necessary to consider the configuration, parameters, and behavior of the ac grids on both sides of the HVDC, as well as the dc line connecting the two stations. Internal insulation of equipment such as transformers and bushings

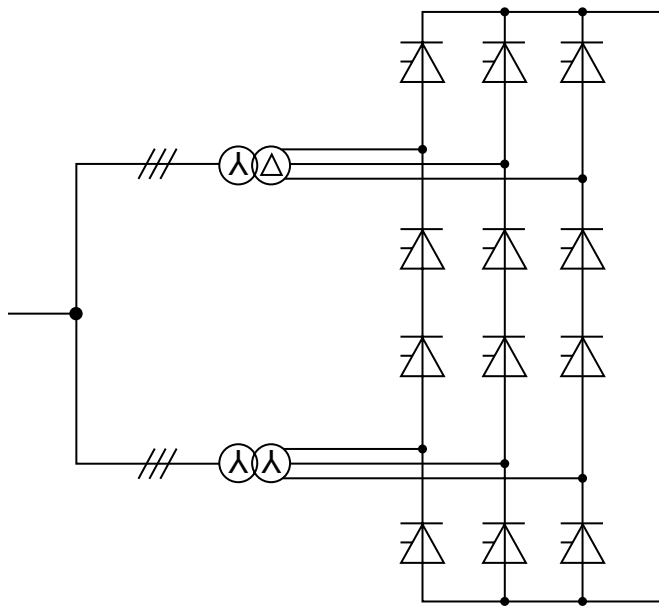


FIGURE 5.3 Transformers and valves in a 12-pulse converter bridge.

must take voltage gradient distribution in solid and mixed dielectrics into account. The main insulation of a converter transformer has to withstand combined ac and dc voltage stresses. Substation clearances and creepage distances must be adequate. Standards for indoor and outdoor clearances and creepage distances are being promulgated [11]. Direct-current electric fields are static in nature, thus enhancing the pollution of exposed surfaces. This pollution, particularly in combination with water, can adversely influence the voltage-withstand capability and voltage distribution of the insulating surfaces. In converter stations, therefore, it is often necessary to engage in adequate cleaning practices of the insulators and bushings, to apply protective greases, and to protect them with booster sheds. Insulation problems with extra-high-voltage dc bushings continue to be a matter of concern and study [12, 13].

A specific issue with long-distance dc transmission is the use of ground return. Used during contingencies, ground (and sea) return can increase the economy and availability of HVDC transmission. The necessary electrodes are usually located at some distance from the station, with a neutral line leading to them. The related neutral bus, switching devices, and protection systems form part of the station. Electrode design depends on the soil or water conditions [14, 15]. The National Electric Safety Code (NESC) does not allow the use of earth as a permanent return conductor. Monopolar HVDC operation in ground-return mode is permitted only under emergencies and for a limited time. Also environmental issues are often raised in connection with HVDC submarine cables using sea water as a return path. This has led to the recent concept of metallic return path provided by a separate low-voltage cable. The IEEE-PES is working to introduce changes to the NESC to better meet the needs of HVDC transmission while addressing potential side effects to other systems.

Mechanical switching devices on the dc side of a typical bipolar long-distance converter station comprise metallic return transfer breakers (MRTB) and ground return transfer switches (GRTS). No true dc breakers exist, and dc fault currents are best and most swiftly interrupted by the converters themselves. MRTBs with limited dc current interrupting capability have been developed [16]. They include commutation circuits, i.e., parallel reactor/capacitor (L/C) resonance circuits that create artificial current zeroes across the breaker contacts. The conventional grid-connecting equipment in the ac switchyard of a converter station is covered in the preceding sections. In addition, reactive power compensation and harmonic filter equipment are connected to the ac buses of the converter station. Circuit breakers used



FIGURE 5.4 A 200 MW HVDC back-to-back converter station at Sidney, Nebraska (photo courtesy of Siemens).

for switching these shunt capacitors and filters must be specially designed for capacitive switching. A back-to-back converter station does not need any mechanical dc switching device.

Figure 5.4 through Figure 5.7 show photos of different converter stations. The back-to-back station shown in Figure 5.4 is one of several asynchronous links between the western and eastern North American power grids. The photo shows the control building (next to the communication tower), the valve hall attached to it, the converter transformers on both sides, the ac filter circuits (near the centerline), and the ac buses (at the outer left and right) with the major reactive power compensation and temporary overvoltage (TOV) suppression equipment that was used in this low-short-circuit-ratio installation. The valve groups shown in Figure 5.5 are arranged back to back, i.e., across the aisle in the same room.

Figure 5.6 shows the valve hall of a ± 500 -kV long-distance transmission system, with valves suspended from the ceiling for better seismic-withstand capability. The converter station shown in Figure 5.7 is the south terminal of the Nelson River ± 500 -kV HVDC transmission system in Manitoba, Canada. It consists of two bipoles commissioned in stages from 1973 to 1985. The dc yard and line connections can be seen on the left side of the picture, while the 230-kV ac yard with harmonic filters and converter transformers is on the right side. In total, the station is rated at 3854 MW.

5.2 FACTS Controllers

The acronym FACTS stands for “flexible ac transmission systems.” These systems add some of the virtues of dc, i.e., phase independence and fast controllability, to ac transmission by means of electronic controllers. Such controllers can be shunt or series connected or both. They represent variable reactances or ac voltage sources. They can provide load flow control and, by virtue of their fast controllability, damping of power swings or prevention of subsynchronous resonance (SSR).

Typical ratings of FACTS controllers range from about thirty to several hundred MVar. Normally they are integrated in ac substations. Like HVDC converters, they require controls, cooling systems, harmonic filters, transformers, and related civil works.

Static VAr compensators (SVC) are the most common shunt-connected controllers. They are, in effect, variable reactances. SVCs have been used successfully for many years, either for load (flicker) compensation of large industrial loads (arc furnaces, for example) or for transmission compensation in utility systems. Figure 5.8 shows a schematic one-line diagram of an SVC, with one thyristor-controlled reactor,



FIGURE 5.5 600 MW HVDC back-to-back converter valves (photo courtesy of Siemens).

two thyristor-switched capacitors, and one harmonic filter. The thyristor controller and switches provide fast control of the overall SVC reactance between its capacitive and inductive design limits. Due to the network impedance, this capability translates into dynamic bus voltage control. As a consequence, the SVC can improve transmission stability and increase power transmission limits across a given path. Harmonic filter and capacitor banks, reactors (normally air core), step-down transformers, breakers and disconnect switches on the high-voltage side, as well as heavy-duty buswork on the medium-voltage side characterize most SVC stations. A building or an e-house with medium-voltage wall bushings contains the power electronic (thyristor) controllers. The related cooler is usually located nearby.

A new type of controlled shunt compensator, a static compensator called STATCOM, uses voltage-sourced converters with high-power gate-turn-off thyristors (GTO), or IGBT [17, 18]. [Figure 5.9](#) shows the related one-line diagram. STATCOM is the electronic equivalent of the classical (rotating) synchronous condenser, and one application of STATCOM is the replacement of old synchronous condensers. The need for high control speed and low maintenance can support this choice. Where the STATCOM's lack of inertia is a problem, it can be overcome by a sufficiently large dc capacitor. STATCOM requires



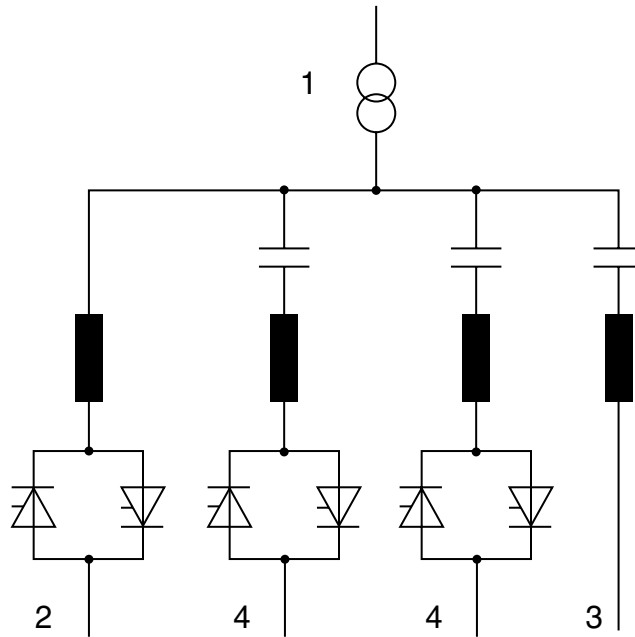
FIGURE 5.6 Valve hall of a ± 500 kV, 1200 MW long-distance HVDC Converter Station (photo courtesy of Siemens).



FIGURE 5.7 Dorsey terminal of the Nelson River HVDC transmission system (photo courtesy of Manitoba Hydro).

fewer harmonic filters and capacitors than an SVC, and no reactors at all. This makes the footprint of a STATCOM station significantly more compact than that of the more conventional SVC.

Like the classical fixed series capacitors (SC), thyristor-controlled series capacitors (TCSC) [19, 20] are normally located on insulated platforms, one per phase, at phase potential. Whereas the fixed SC



- 1 Transformer
- 2 Thyristor- controlled reactor (TCR)
- 3 Fixed connected capacitor/filter bank
- 4 Thyristor-switched capacitor bank(TSC)

FIGURE 5.8 One-line diagram of a Static VAR Compensator (SVC).

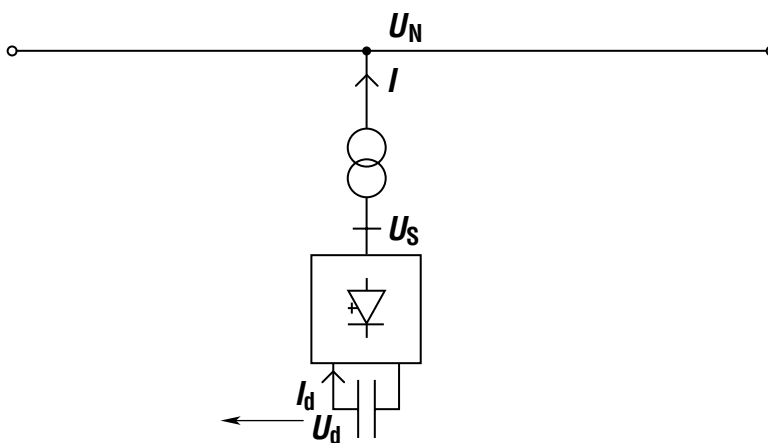


FIGURE 5.9 One-line diagram of a voltage sourced Static Compensator (STATCOM).

compensates a fixed portion of the line inductance, TCSC's effective capacitance and compensation level can be varied statically and dynamically. The variability is accomplished by a thyristor-controlled reactor connected in parallel with the main capacitor. This circuit and the related main protection and switching

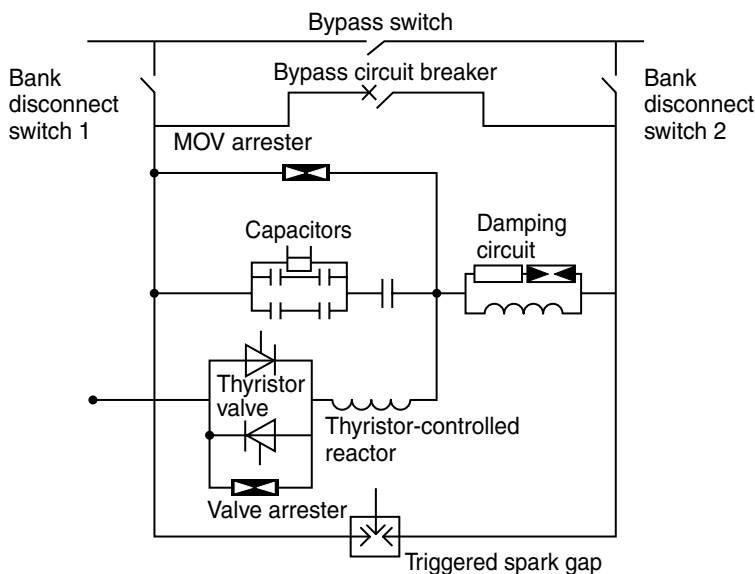


FIGURE 5.10 Schematic diagram of one phase of the Serra da Mesa (Brazil) Thyristor-controlled Series Capacitor (TCSC).

components are shown in Figure 5.10. The thyristors are located in weatherproof housings on the platforms. Communication links exist between the platforms and ground. Liquid cooling is provided through ground-to-platform pipes made of insulating material. Auxiliary platform power, where needed, is extracted from the line current via current transformers (CTs). Like most conventional SCs, TCSCs are typically integrated into existing substations. Upgrading an existing SC to TCSC is generally possible. A new development in series compensation is the thyristor-protected series compensator (TPSC). The circuit is basically the same as for TCSC, but without any controllable reactor and forced thyristor cooling. The thyristors of a TPSC are used only as a bypass switch to protect the capacitors against overvoltage, thereby avoiding large MOV arrester banks with relatively long cool-off intervals.

While SVC and STATCOM controllers are shunt devices, and TCSCs are series devices, the so-called unified power flow controller (UPFC) is a combination of both [21]. Figure 5.11 shows the basic circuit. The UPFC uses a shunt-connected transformer and a transformer with series-connected line windings, both interconnected to a dc capacitor via related voltage-source-converter circuitry within the control building. A more recent FACTS station project [22–24] involves similar shunt and series elements as the UPFC, and this can be reconfigured to meet changing system requirements. This configuration is called a convertible static compensator (CSC).

The ease with which FACTS stations can be reconfigured or even relocated is an important factor and can influence the substation design [25, 26]. Changes in generation and load patterns can make such flexibility desirable.

Figure 5.12 through Figure 5.17 show photos of FACTS substations. Figure 5.12 shows a 500-kV ac feeder (on the left side), the transformers (three single-phase units plus one spare), the medium-voltage bus, and three thyristor-switched capacitor (TSC) banks, as well as the building that houses the thyristor switches and controls.

The SVC shown in Figure 5.13 is connected to the 420-kV Norwegian ac grid southwest of Oslo. It uses thyristor-controlled reactors (TCR) and TSCs, two each, which are visible together with the 9.3-kV high-current buswork on the right side of the building.

Figure 5.14 and Figure 5.15 show photos of two 500-kV TCSC installations in the U.S. and Brazil, respectively. In both, the platform-mounted valve housings are clearly visible. Slatt (U.S.) has six equal

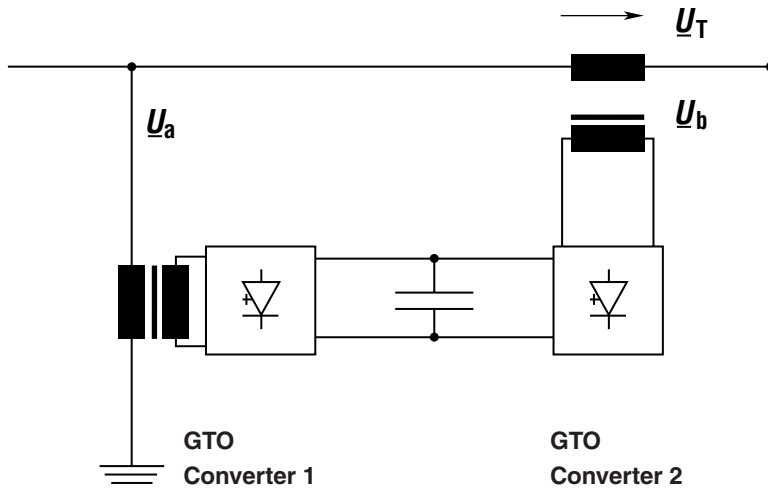


FIGURE 5.11 One-line diagram of a Unified Power Flow Controller (UPFC).



FIGURE 5.12 500 kV, 400 MVar SVC at Adelanto, California (photo courtesy of Siemens).

TCSC modules per phase, with two valves combined in each of the three housings per bank. At Serra da Mesa (Brazil), each platform has one single valve housing.

Figure 5.16 shows an SVC being relocated. The controls and valves are in containerlike housings, which allow for faster relocation. Figure 5.17 shows the world's first UPFC, connected to AEP's Inez substation in eastern Kentucky. The main components are identified and clearly recognizable. Figure 5.18 depicts a CSC system at the 345-kV Marcy substation in New York state.

5.3 Control and Protection System

Today's state-of-the-art HVDC and FACTS controls — fully digitized and processor-based — allow steady-state, quasi steady-state, dynamic, and transient control actions and provide important equipment

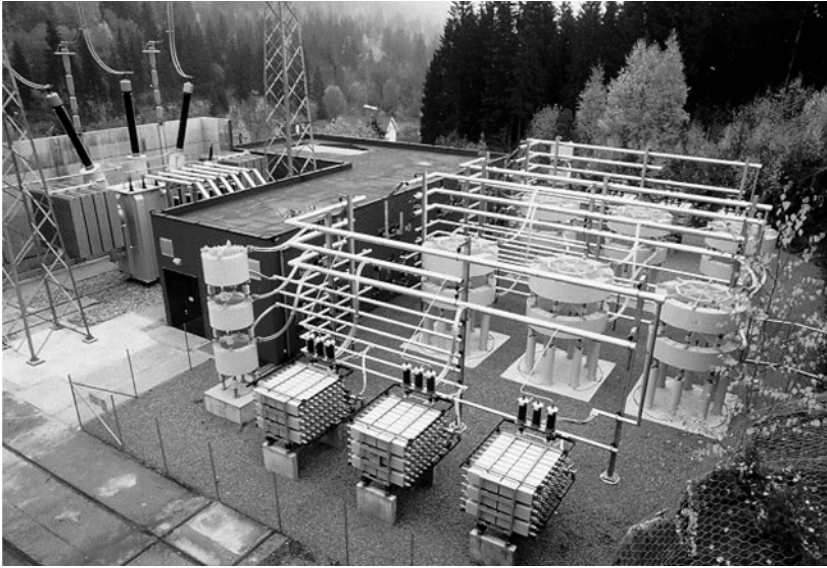


FIGURE 5.13 420 kV, ± 160 MVar SVC at Sylling, Norway (photo courtesy of ABB).

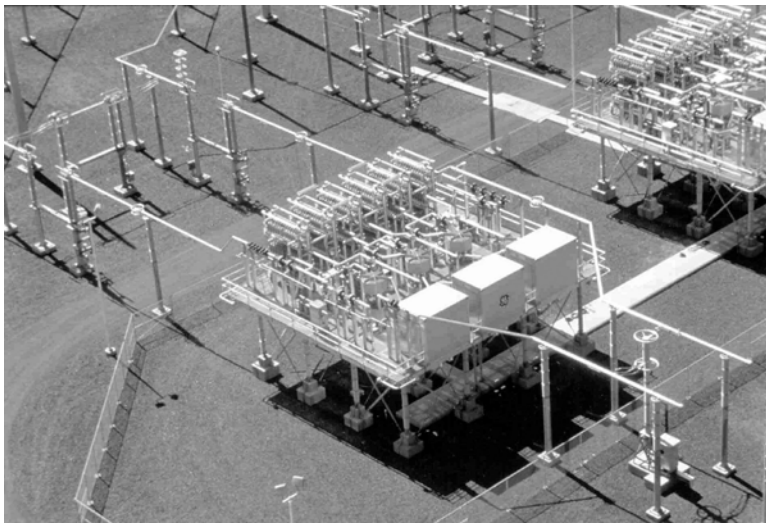


FIGURE 5.14 Aerial view of BPA's Slatt, Oregon, 500kV TCSC (photo courtesy of GE).

and system protection functions. Fault monitoring and sequence-of-event recording devices are used in most power electronics stations. Typically, these stations are remotely controlled and offer full local controllability as well. Man-machine interfaces are highly computerized, with extensive supervision and control via monitor and keyboard. All of these functions exist in addition to the basic substation secondary systems described in [Chapters 6 and 7](#).

HVDC control and protection algorithms are usually rather complex. Real power, reactive power, ac bus frequency and voltage, startup and shutdown sequences, contingency and fault-recovery sequences, remedial action schemes, modulation schemes for system oscillation and SSR damping, and loss of communication are some of the significant control parameters and conditions. Fast dynamic performance is standard. Special voltage vs. current (v/i) control characteristics are used for converters in multiterminal



FIGURE 5.15 TCSC Serra da Mesa, FURNAS, Brazil, 500kV, 107MVar, $(1...3) \times 13.17\text{W}$ (photo courtesy of Siemens).



FIGURE 5.16 Static Var Compensator is relocated where the system needs it (photo courtesy of ALSTOM T&D Power Electronic Systems).

HVDC systems to allow safe operation even under loss of interstation communication. Furthermore, HVDC controls provide equipment and system protection, including thyristor overcurrent, thyristor overheating, and dc line fault protection. Control and protection reliability are enhanced through redundant and fault-tolerant design. HVDC stations can often be operated from different control centers.

[Figure 5.19](#) illustrates the basic control levels and hierarchy used in one terminal of a bipolar HVDC long-distance transmission scheme. Valve control at process level is based on phase-angle control, i.e.,

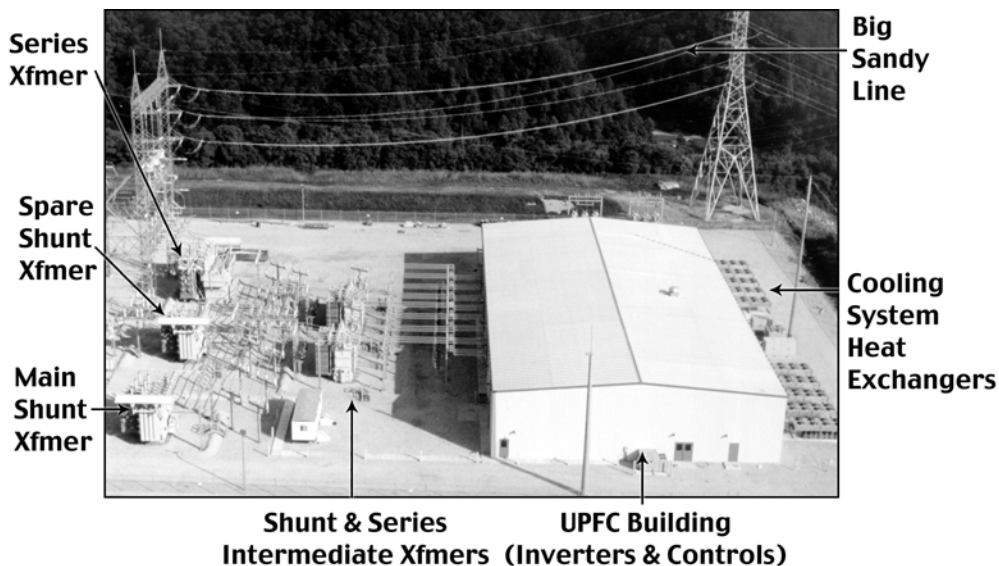


FIGURE 5.17 UPFC at Inez substation (photo courtesy of American Electric Power).



FIGURE 5.18 Convertible Static Compensator (CSC) at NYPA's 345kV Marcy, New York substation (photo courtesy of New York Power Authority).

gating of thyristors (or other semiconductors) precisely timed with respect to the related ac phase voltages. The phase angles determine the converter dc voltages and, per Ohm's law, dc currents and load flow.

Figure 5.20 shows the local control interface of a back-to-back HVDC converter station used for power transmission between nonsynchronous grids. Figure 5.21 shows a photo taken during the functional testing of the control and protection hardware against a real-time simulator for a major long-distance HVDC scheme. Figure 5.22 shows a typical control monitor screen layout displaying a bipolar HVDC system overview.

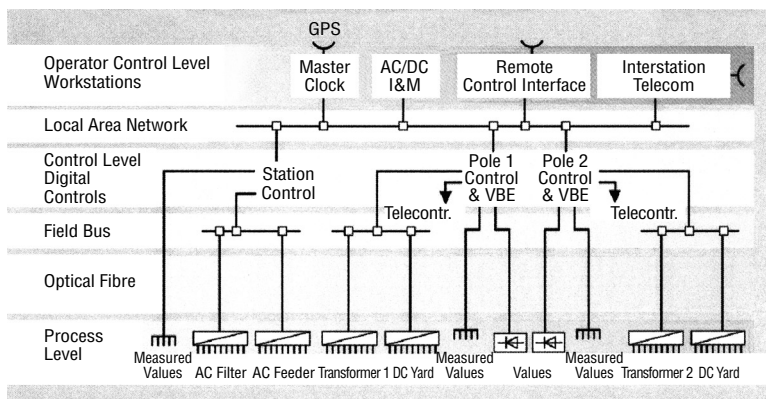


FIGURE 5.19 HVDC control hierarchy, one station.



FIGURE 5.20 Local control desk of a 600 MW back-to-back converter station (photo courtesy of Siemens).

The protection zones of one pole of an HVDC converter station are shown in Figure 5.23. Each protection zone is covered by at least two independent protective units — the primary protective unit and the secondary (backup) protective unit. Protection systems are separated from the control software and hardware. Some control actions are initiated by the protection scheme via signals to the control system.

The control and protection schemes of FACTS stations are tailored to the related circuits and tasks. Industrial SVCs have open-loop, direct, load-compensation control. In transmission systems, FACTS controllers are designed to provide closed-loop steady-state and dynamic control of reactive power and bus voltage, as well as some degree of load flow control, with modulation loops for stability and SSR mitigation. In addition, the controls include equipment and system protection functions.

With SVC and TCSC, the phase-angle control determines the effective shunt and series reactance, respectively. This fast reactance control, in turn, has the steady-state and dynamic effects listed above.



FIGURE 5.21 Controls for a ± 500 kV, 1800MW HVDC; function test (photo courtesy of Siemens).

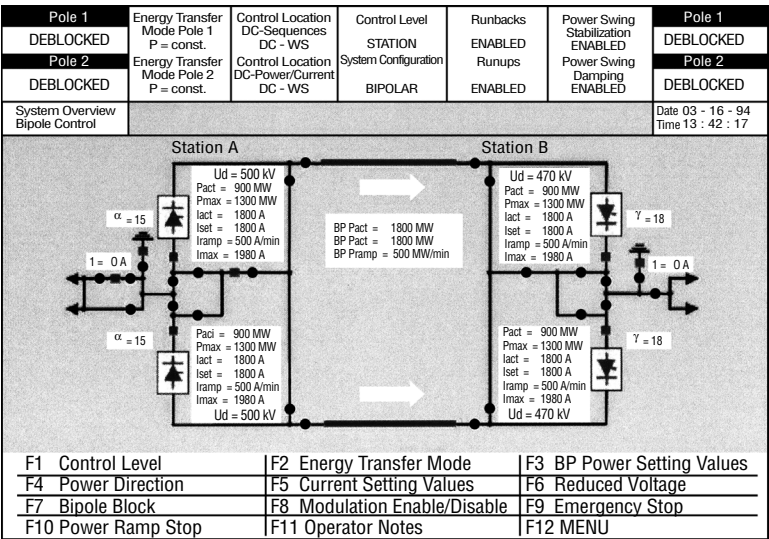


FIGURE 5.22 Operator workstation, typical screen layout for a bipolar HVDC system overview.

STATCOM control is phase-angle-based inverter ac voltage output control. The ac output is essentially in phase with the system voltage. The amplitude determines whether the STATCOM acts in a capacitive or inductive mode.

Most controllers included here have the potential to provide power system damping, i.e., to improve system stability. By the same token, if not properly designed, they may add to or even create system undamping, especially subsynchronous resonance (SSR). It is imperative to include proper attention to SSR in the control design and functional testing of power electronic stations, especially in the vicinity of existing or planned turbogenerators.

Principally, the control and protection systems described above comprise the following distinctive hardware and software subsystems:

- Valve firing and monitoring circuits
- Main (closed-loop) control
- Open-loop control (sequences, interlocks, etc.)

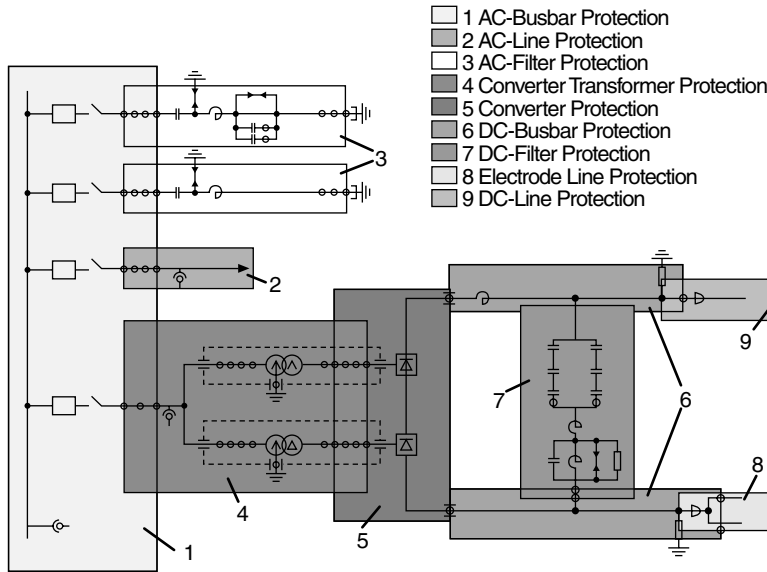


FIGURE 5.23 HVDC converter station protection zones (one pole).

- Protective functions
- Monitoring and alarms
- Diagnostic functions
- Operator interface and communications
- Data handling

5.4 Losses and Cooling

Valve losses in high-voltage power electronic substations are comparable in magnitude to those of the associated transformers. Typical HVDC converter efficiency exceeds 99%. This means that the losses in each terminal of a 1000-MW long-distance transmission system can approach 10 MW. Those of a 200-MW back-to-back station (both conversions ac-dc-ac in the same station) can be approximately 4 MW. The valves' share would be about 5 MW and 2 MW, respectively. Deionized water circulated in a closed loop is generally used as primary valve coolant. Various types of dry or evaporative secondary coolers dissipate the heat, usually into the surrounding air.

As opposed to the relatively broad distribution of losses in transformers, power electronic valve equipment includes areas of extreme loss density. Almost all losses occur in semiconductor wafers and snubber resistors. This loss density and the location of the converter valves inside a building make special cooling techniques necessary.

Standard procedures to determine and evaluate high-voltage power electronic substation losses, HVDC converter station losses in particular, have been developed [27].

5.5 Civil Works

High-voltage power electronic substations are special because of the valve rooms and buildings required for converters and controls, respectively. Insulation clearance requirements can lead to very large valve rooms (halls). The valves are connected to the yard through wall bushings. Converter transformers are often placed adjacent to the valve building, with the valve-side bushings penetrating through the walls in order to save space.

The valves require controlled air temperature, humidity, and cleanness inside the valve room. Although the major part of the valve losses is handled by the valve cooling system, a fraction of the same is dissipated into the valve room and adds to its air-conditioning or ventilation load. The periodic fast switching of electronic converter and controller valves causes a wide spectrum of harmonic currents and electromagnetic fields, as well as significant audible noise. Therefore, valve rooms are usually shielded electrically with wire mesh in walls and windows. Electric interference with radio, TV, and communication systems can usually be controlled with power-line carrier filters and harmonic filters.

Sources of audible noise in a converter station include the transformers, capacitors, reactors, and coolers. To comply with the contractually specified audible noise limits within the building (e.g., in the control room) and outdoors (in the yard, at the substation fence), low-noise equipment, noise-damping walls, barriers, and special arrangement of equipment in the yard may be necessary. The theory of audible noise propagation is well understood [28], and analytical tools for audible noise design are available [29]. Specified noise limits can thus be met, but doing so may have an impact on total station layout and cost. Of course, national and local building codes also apply. In addition to the actual valve room and control building, power electronic substations typically include rooms for coolant pumps and water treatment, for auxiliary power distribution systems, air conditioning systems, battery rooms, and communication rooms.

Extreme electric power flow densities in the valves create a certain risk of fire. Valve fires with more or less severe consequences have occurred in the past [30]. Improved designs as well as the exclusive use of flame-retardant materials in the valve, coordinated with special fire detection and protection devices, reduce this risk to a minimum [31]. The converter transformers have fire walls in between and dedicated sprinkler systems around them as effective fire-fighting equipment.

Many high-voltage power electronic stations have spare transformers to minimize interruption times following a transformer failure. This leads to specific arrangements and bus configurations or extended concrete foundations and rail systems in some HVDC converter stations.

Some HVDC schemes use outdoor valves with individual housings. They avoid the cost of large valve buildings at the expense of a more complicated valve maintenance. TCSC stations also have similar valve housings on insulated platforms together with the capacitor banks and other equipment.

5.6 Reliability and Availability

Power electronic systems in substations have reached levels of reliability and availability comparable with the balance of substation components. System availability is influenced by forced outages due to component failures and by scheduled outages for preventive maintenance or other purposes. By means of built-in redundancy, detailed monitoring, self-supervision of the systems, segmentation and automatic switch-over strategies, together with consistent quality control and a prudent operation and maintenance philosophy, almost any level of availability is achievable. The stations are usually designed for unmanned operation. The different subsystems are subjected to an automatic internal control routine, which logs and evaluates any deviations or abnormalities and relays them to remote control centers for eventual actions if necessary. Any guaranteed level of availability is based on built-in redundancies in key subsystem components. With redundant thyristors in the valves, spare converter transformers at each station, a completely redundant control and protection system, available spare parts for other important subsystems, maintenance equipment, and trained maintenance personnel at hand, an overall availability level as high as 99% can be attained, and the average number of annual forced outages can be kept below five.

The outage time for preventive maintenance of the substation depends mainly on a utility's practices and philosophy. Most of the substation equipment, including control and protection, can be overhauled in coordination with the valve maintenance, so that no additional interruption of service is necessary. Merely a week annually is needed per converter station of an HVDC link.

Because of their enormous significance in the high-voltage power transmission field, HVDC converters enjoy the highest level of scrutiny, systematic monitoring, and standardized international reporting of

reliability design and performance. CIGRE has developed a reporting system [32] and publishes biannual HVDC station reliability reports [33]. At least one publication discusses the importance of substation operation and maintenance practices on actual reliability [34]. The IEEE has issued a guide for HVDC converter reliability [35]. Other high-voltage power electronic technologies have benefited from these efforts as well. Reliability, availability, and maintainability (RAM) have become frequent terms used in major high-voltage power electronic substation specifications [36] and contracts.

High-voltage power electronic systems warrant detailed specifications to assure successful implementation. In addition to applicable industry and owner standards for conventional substations and equipment, many specific conditions and requirements need to be defined for high-voltage power electronic substations. To facilitate the introduction of advanced power electronic technologies in substations, the IEEE and IEC have developed and continue to develop applicable standard specifications [37, 38].

Operation and maintenance training are important for the success of high-voltage power electronic substation projects. A substantial part of this training is best performed on site during commissioning. The IEEE and other organizations have, to a large degree, standardized high-voltage power electronic component and substation testing and commissioning procedures [39–41]. Real-time digital system simulators have become a major tool for the off-site function tests of all controls, thus reducing the amount of actual on-site testing. Nonetheless, staged fault tests are still performed with power electronic substations including, for example, with the Kayenta TCSC [42].

5.7 Future Trends

For interconnecting asynchronous ac networks and for transmission of bulk energy over long distances, HVDC systems remain economically, technically, and environmentally the preferred solution at least in the near future. One can expect continued growth of power electronics applications in transmission systems. Innovations such as the voltage-sourced converter [43] or the capacitor-commutated converter [44], active filters, outdoor valves [45], or the transformerless converter [46] may reduce the complexity and size of HVDC converter stations [47]. Voltage-sourced converter technology combined with innovative dc cables may make converter stations economically viable also at lower power levels (up to 300 MW).

New and more economical FACTS technologies may be introduced. Self-commutated converters and active filters will change the footprint of high-voltage power electronic substations. STATCOMs may eventually replace rotating synchronous condensers. TCSCs or UPFCs may replace phase-shifting transformers to some degree. New developments such as electronic transformer tap changers, semiconductor breakers, electronic fault-current limiters and arresters may even affect the “conventional” parts of the substation. As a result, the high-voltage power electronic substations of the future will be more common, more effective, more compact, easier to relocate, and found in a wider variety of settings.

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